On coherent particle production in central 4.3 A Gev/c Mg-Mg collisions

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Abstract

Features of dense groups, or spikes, of negative pions produced in Mg-Mg collisions at 4.3 GeV/c/nucleon are studied to search for a coherent, Čerenkov-like, mechanism of particle production process. We investigate the distributions of spike centers and, for the first time, the energy spectra of particles in spikes. The spike-center distributions are obtained to exhibit the structure due to the coherent gluon-jet emission dynamics. This structure is similar to that observed recently for all-charged-particle spikes in hadronic and nuclear interactions. The energy distribution within spikes is found to have a significant peak over the inclusive background, while the inclusive spectrum shows exponential decrease with two characteristic values of average kinetic energy. The value of the peak energy and its width are in a good agreement with those expected for pions produced in a nuclear medium in the framework of the Čerenkov quantum approach. The peak energy obtained is consistent with the value of the cross-section maximum observed in coincidence experiments of nucleon-nucleus interactions.

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1 Introduction

A coherent component of particle production mechanism, Čerenkov-like radiation, in high energy particle collisions has been introduced a long time ago. The idea of mesonic [1] and scalar (pionic) [2] radiation has recently been a subject of the systematic analysis of production of mesons in high-energy pion-nucleon scattering in nuclear medium in terms of classical quantum mechanics [3]. Characteristic signatures of the Čerenkov mechanism, such as the differential cross-sections and angle-energy correlations of produced particles, have been predicted.

Another approach of the Čerenkov-like radiation in strong interactions was suggested within the QCD based coherent gluon-jet emission model [4]. In this model the pseudorapidity distributions of centers of particle dense groups, called spikes, are proposed to be investigated. The distributions of spike centers are predicted to have two peaks due to destructive interference for quarks of the same colour (pp collisions) or to be singly peaked due to constructive interference for quarks of different colour (e.g. $p\bar{p}$ interactions). Recent observations in hadronic [5] and nuclear [6] interactions are found to be in agreement with these predictions.

In this letter we search for dynamics of spike formation process using negative pions from collisions of relativistic nuclei. The finite size gluon-jet production mechanism is applied to obtain the coherent dynamics, while further analysis deals with the energy spectrum of emitted pions in the framework of the nuclear pionic Čerenkov-like radiation (NPICR) approach.

It is worth to mention that spikes have been extensively investigated last years using stochastic picture of particle production mechanism, namely intermittency phenomenon has been searched for and obtained in all types of collisions [7]. In our studies [8], we also found the intermittency effect leading to multifractality and, then, to a conclusion of a possible non-thermal phase transition during the cascading. The latter observation have been confirmed in different reactions [9].

2 Experimental details

The results presented here are based on the experimental data obtained after processing the pictures from the 2m Streamer Chamber SKM-200 [10] with a magnesium target placed inside. The chamber was installed in a 0.8 T magnetic field and it was irradiated with a beam of relativistic magnesium nuclei with momentum 4.3 GeV/c per nucleon at the Dubna JINR Synchrophasotron. A trigger selected central collisions has been used in the experiment. The trigger started the Chamber if there were no charged or neutral projectile fragments (momentum per nucleon required to be greater than 3 GeV/c) emitted in a forward cone of 2.4°. A more detailed description of the set-up design and data reduction procedure are given elsewhere [10–12]. Systematic errors related to the trigger effects, low-energy pion and proton detection, the admixture of electrons, secondary interactions in the target nucleus etc. have been considered in detail earlier and the total contribution is estimated do not exceed 3% [11, 13].

A total of 14218 Mg-Mg events were found to meet the above centrality criterion. In the utilized sample only negative charged particles (mainly π^- mesons with a portion of some 1% kaons) have been studied. The average measurement error in momentum $\langle \varepsilon_p/p \rangle$ was about 1.5% and that in the production angle determination was $\langle \varepsilon_\vartheta \rangle \simeq 0.1°$. The particles were selected in the pseudorapidity ($\eta = -\ln\tan\frac{1}{2}\vartheta$) window of $\Delta\eta = 0.4 - 2.4$ (in the laboratory frame) in which the angular measurement accuracy does not exceed 0.01 in η units. The mean multiplicity of the selected pions is 6.70 ± 0.02.

The choice of π^- mesons for the analysis presented is due to the fact that they dominate among the produced particles and are well identified. On the other hand, the production of pions is predominant process at the energies of the Dubna Synchrophasotron and, therefore, they carry important information about the dynamics of collisions. The inclusive characteristics of π^-'s in the reaction under investigation have been studied earlier in Ref. [12]. Increase of statistics by more than twice allows analysing of more detail features of particle production process.

To overcome an influence of the shape of the pseudorapidity distribution on the results we use the "cumulative variable",

$$\widetilde{\eta}\,(\eta) \;=\int_{\eta_{\min}}^{\eta} \rho(\eta')\,\mathrm{d}\eta' \Bigg/ \int_{\eta_{\min}}^{\eta_{\max}} \rho(\eta')\,\mathrm{d}\eta' \;, \tag{1}$$

with the uniform spectrum $\rho(\widetilde{\eta})$ within the interval [0,1], as advocated in Ref. [14]. This transformation makes possible to compare results from different experiments.

The spikes are extracted in each event from the ordered pseudorapidities which are scanned with a fixed pseudorapidity interval (bin) of size $\delta\widetilde{\eta}$. The spikes with definite number of particles δn, hit in the bin, are determined and then the distributions of centers of spikes, averaged over all events, are obtained. The center of spike is defined by $\widetilde{\eta}_0 = (1/\delta n)\sum_{j=1}^{\delta n}\widetilde{\eta}_j$.

To reveal dynamical correlations, the $\widetilde{\eta}_0$-distribution is compared with analogous distributions obtained from the simulated pseudorapidity single-particle spectrum $\rho(\widetilde{\eta})$ without any input information about particle correlations. The simulation procedure was as follows. According to the multiplicity distribution of the data sample, the number of particles were randomly generated. Then, the pseudorapidities were distributed in accordance with the experimental $\widetilde{\eta}$-spectrum and corresponding to the generated multiplicity. The total number of the simulated events was about 1.5 million, much more than 100 times the

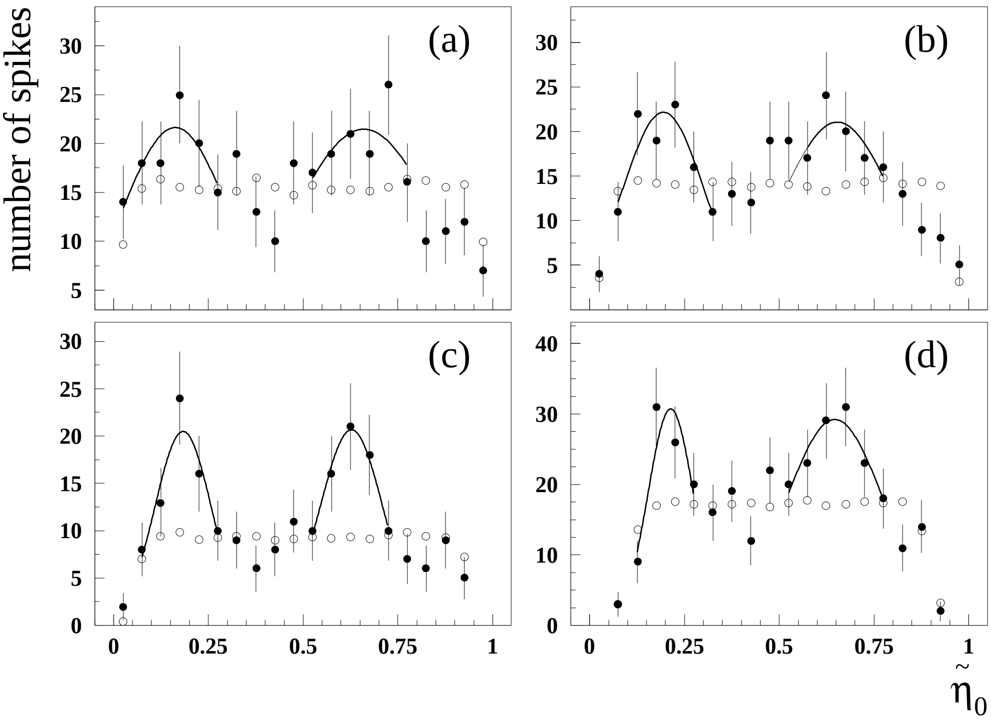

Figure 1: Experimental (•) and simulated (∘) spike-center distributions for different $\delta\widetilde{\eta}$-bins and δn-multiplicities: **(a)** $\delta\widetilde{\eta} = 0.05,\ \delta n = 4$, **(b)** $\delta\widetilde{\eta} = 0.1,\ \delta n = 5$, **(c)** $\delta\widetilde{\eta} = 0.15,\ \delta n = 6$, **(d)** $\delta\widetilde{\eta} = 0.25,\ \delta n = 7$. The curves represent Gaussian fits.

experimental events. Evidently, the obtained sample represents results from independent particle emission process.

3 The results

3.1 Spike-center distributions

Fig. 1 shows the pseudorapidity spike-center $\widetilde{\eta}_0$-distributions for four different size $\delta\widetilde{\eta}$-bins and for spikes of various multiplicities δn. A two-peak structure of the measured distributions (solid circles) with the peaks in the neighbourhood of the same $\widetilde{\eta}_0$ is seen independent of the width and multiplicity of spike. The shape of the distributions is in agreement with the structure predicted by the coherent gluon-jet emission model [4] and is similar to that observed earlier in hadronic interactions [5] and by us in C-Cu collisions [6].

In order to estimate the positions of the peaks and the distance between them, we fit these two bumps with Gaussians and average over different spikes.

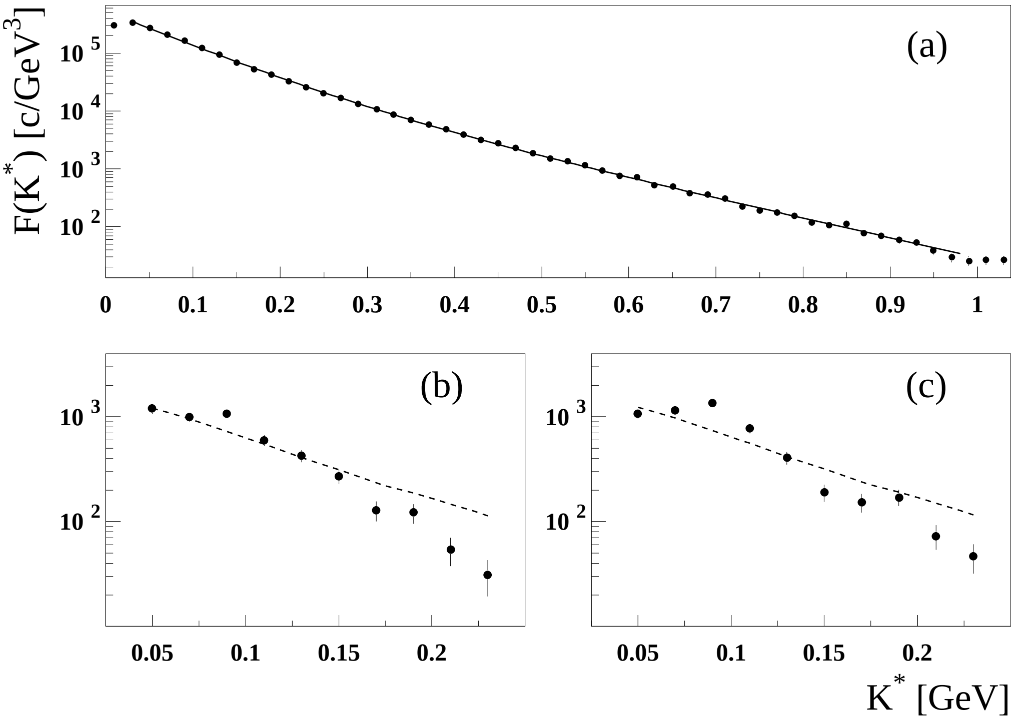

Figure 2: Inclusive kinetic energy distribution **(a)** and analogous distributions for spikes of **(b)** $\delta\widetilde{\eta} = 0.1,\ \delta n = 6$ and **(c)** $\delta\widetilde{\eta} = 0.15,\ \delta n = 7$. The solid line represents the exponential fit with Eq. (3), the dashed lines show the inclusive background.

The peaks are found to be placed at $\widetilde{\eta}_0 \approx 0.19$ and 0.63, or at $\eta_0 = 0.89 \pm 0.03(\mathrm{stat}) \pm 0.08(\mathrm{syst})$ and $1.63 \pm 0.05(\mathrm{stat}) \pm 0.10(\mathrm{syst})$. They are separated by the d_0 interval,

$$d_0 = 0.75 \pm 0.06(\mathrm{stat}) \pm 0.13(\mathrm{syst}) \tag{2}$$

in η units. This value is close to those from the above mentioned nuclear and hadronic interactions.

The dynamical origin of the structure obtained comes from a comparison of the experimental $\widetilde{\eta}_0$-distributions with those based on the above described simulated events (open circles in Fig. 1). No peaks are seen in the simulated distributions levelling off at the background, far away from the measured peaks. This points to the dynamical effect in the formation of spikes due to the coherent gluon radiation picture.

In order to assess the reliability of the results obtained, we studied the influence of the $\Delta\eta$-range used and the experimental error $\langle\varepsilon_\vartheta\rangle$ in the measurements of the polar angle ϑ. Varying the $\Delta\eta$ range and the error $\langle\varepsilon_\vartheta\rangle$ we found the structure of the distributions unchanged and the positions of the two peaks and the distance d_0 to be within the above shown errors, in support of the conclusions made.

3.2 In-spike energy spectra

The obtained strong signal of the coherent emission dynamics allows further search for its manifestations in the energy distributions as it is predicted in the NPICR approach [3]. In this model, the energy spectra of pions emitted through the coherent Čerenkov-like mechanism when a few GeV proton passes the nuclear medium is predicted to have a peak. This peak is expected to appear at 260 MeV when absorption effect is neglected and at 244 MeV otherwise.

In Fig. 2 we compare the c.m.s. inclusive kinetic energy distribution, $F(K^*) = (1/E^*p^*)\,\mathrm{d}N/\mathrm{d}K^*$, with analogous spectra calculated for pions from spikes. Here, E^* and p^* denote, respectively, the particle energy and momentum in the c.m.s. frame.

Using the temperature description, utilized in the last time to characterize a system of excited hadrons [12,15–17], we parametrize the inclusive spectrum (Fig. 2a) by a sum of two exponents,

$$F(K^*) = A_1 \exp(-K^*/T_1) + A_2 \exp(-K^*/T_2)\,, \tag{3}$$

where the temperatures $T_1 < T_2$ characterize [15] the two possible mechanisms of pion production, via Δ-resonance decay and directly, and are related to the pion average kinetic energies. The range of the parametrization shown is limited from below and from above due to detector effects and corresponding requirements on the momenta of pions. The fit gives $T_1 = 65 \pm 1$ MeV and $T_2 = 127 \pm 1$ MeV. These values are, in general, consistent with those obtained from the earlier analysis of the reaction under study [12] and from other experiments [15, 16]. Some difference in the values could be explained if one takes into account the difference in the sizes of the (pseudo)rapidity regions used [15].

The shape of $F(K^*)$ distribution changes when the analysis is extended to spikes, Figs. 2b and c. The energy spectra of particles belonged to spike differ significantly from the exponential law (3) and have now a peaked shape. To extract the NPICR-signal we compare the in-spike energy spectra with renormalized inclusive distribution, or inclusive background, depicted with the dashed lines. The first peak is seen to be over the background with the statistical significance of 2.7 and 4.1 standard deviations in Figs. 2b and 2c, respectively. This peak is located at the kinetic energy $K^* \approx 100$ MeV, or the total energy $E^* \approx 240$ MeV, in accordance with the NPICR prediction.

To estimate the position of the peak and the bump width and to make the results more comparable with the NPICR expectations, the E^*-distributions of particles in spikes of various size $\delta\widetilde{\eta}$-bins and different δn-multiplicities have

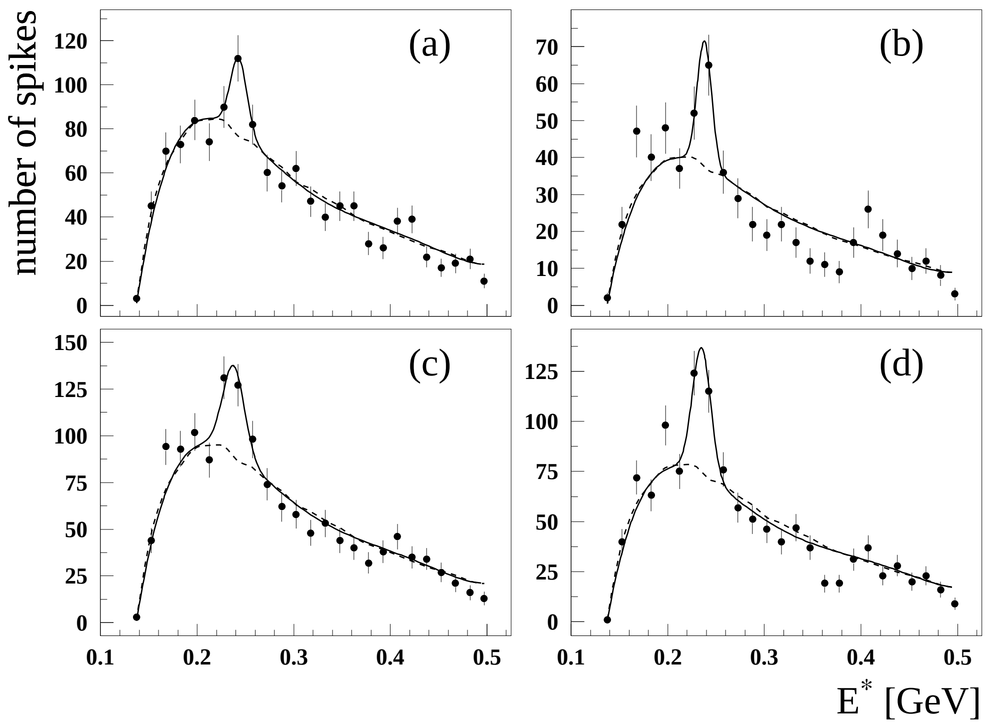

Figure 3: Total energy spectra for spikes of different $\delta\widetilde{\eta}$-bins and multiplicities δn: **(a)** $\delta\widetilde{\eta} = 0.05$, $\delta n = 4$, **(b)** $\delta\widetilde{\eta} = 0.08$, $\delta n = 5$, **(c)** $\delta\widetilde{\eta} = 0.1$, $\delta n = 5$, **(d)** $\delta\widetilde{\eta} = 0.15$, $\delta n = 6$. The solid lines represent the fit (see text), the dashed lines show the inclusive background.

been studied. Fig. 3. represents some of these distributions. The following specific peculiarities are found.

All these E^*-distributions possess a non-exponential behaviour with a pronounced maximum in the vicinity of the value $E^*_{\mathrm{m}} = 240$ MeV regardless the bin size and the multiplicity of spikes. Higher multiplicity of spike is (at fixed $\delta\widetilde{\eta}$ size), more peaks appear. The multi-peak structure is observed for bins with the multiplicities $\delta n > 3$, while at $\delta n \leq 3$ only one peak occurs (not shown).

To reveal the dynamical signal we compare the in-spike energy distributions with the inclusive background (dashed-line). Alike to the above kinetic energy distributions, the value of E^* about 240 GeV is obtained to be most prominently and statistical-significantly peaked over the background. To estimate the background and to parametrize the signal, we use a fifth-order polynomial for the background and the Gaussian for the peak. The solid curve shows the result of this fit. After averaging over various spikes, the position of the peak and its width are found to have the values,

$$E_{\rm m}^* = 238 \pm 3({\rm stat}) \pm 8({\rm syst})\ {\rm MeV}\,, \quad \Gamma_{\rm m} = 10 \pm 3({\rm stat}) \pm 5({\rm syst})\ {\rm MeV}\,, \quad (4)$$

respectively.

The location of the obtained centre of the Gaussian is within the interval of the energies of pions expected from the Čerenkov-like mechanism for incident protons of a few GeV, $224 \leq E_{\rm m} \leq 244$ MeV [3]. The value of $E_{\rm m}^*$ (4) is similar to the position of the peak observed for π^+ invariant mass distribution in analysis of coincidence measurements of (p,n) reaction on carbon target at 1.5 GeV/c in the Δ-resonance excitation region [18], the effect connected with the NPICR mechanism [3]. Also, the width $\Gamma_{\rm m}$ confirms an observation of the Čerenkov radiation signal expected to be $\Gamma \leq 25$ MeV.

4 Conclusions

Recapitulating, in order to search for a coherent, Čerenkov-like emission mechanism of particle production, a study of spikes in relativistic nuclear collisions is carried out with negative pions from central Mg-Mg collisions at a momentum of 4.3 GeV/c per incident nucleon. The spike-center distributions and, for the first time, the energy spectra of particles within spike are investigated for various narrow pseudorapidity bins and different spike multiplicities.

The spike-center distributions are found to possess a double-peak shape that is in agreement with the structure expected from the coherent gluon radiation model. The obtained distance between the peaks as well as the shape of the distributions are similar to those observed recently in analogous studies of charged particle spikes in hadronic and relativistic nuclear interactions. The dynamical effect in the spike-center distributions is revealed by comparison with independent particle-emission model, where no peaks are seen.

The coherent character of particle-production mechanism is confirmed by studying energy distributions. The inclusive energy spectra show monotonic exponential decrease with two specific temperatures, while the in-spike energy distributions are obtained to exhibit a peak at the position and of the width both consistent with the values expected from the theoretical calculations based on the hypothesis of nuclear pionic Čerenkov radiation. The value of the peak energy is close to the recently observed maximum in the differential cross-sections studied in the coincidence experiments of a few GeV nucleon-nucleus interactions.

The results of the presented analysis signalize the coherent emission to be a complementary mechanism to the stochastic scenario of hadroproduction. Furthermore, the similarity of the spike-center distributions obtained for like-charged particles in the presented paper with those for all-charged-particle spikes in the earlier studies indicates important contributions of the coherent mechanism to formation of Bose-Einstein correlations [19]. It is worth to mention that, in comparison to stochastic (intermittency) dynamics, the origin of which remains still unclear [7], the coherent emission has definite underlying dynamics. All this gives evidence for the necessity of further efforts in studying existing experimental data.

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References

[1] W. Wada, Phys. Rev. 75 (1949) 981; D. Ivanenko and V. Gurgenidze, Dokl. Akad. Nauk SSSR 67 (1949) 997; D.I. Blokhintsev and V.L Indenbohm, ZhETF 20 (1950) 1123.

[2] W. Czyż and S.L. Glashow, Nucl. Phys. 20 (1960) 309; G. Yekutieli, Nuovo Cim. 13 (1959) 446, 1306(E); P. Smrž, Nucl. Phys. 35 (1962) 165.

[3] D.B. Ion and W. Stoker, Phys. Rev. C 48 (1993) 1172, Phys. Rev. C 52 (1995) 3332, and refs. therein.

[4] I.M. Dremin, JETP Lett. 30 (1979) 140; Sov. J. Part. Nucl. 18 (1987) 31.

[5] I.M. Dremin *et al.*, Sov. J. Nucl. Phys. 52 (1990) 536; N.M. Agababyan *et al.*, EHS/NA22 Collab., Phys. Lett. B 389 (1996) 397; S.-S. Wang, R. Liu, Z.-M. Wang, Phys. Lett. B 427 (1998) 385.

[6] G.L. Gogiberidze, L.K. Gelovani, E.K. Sarkisyan, Phys. Lett. B 430 (1998) 368.

[7] E.A. De Wolf, I.M. Dremin, W. Kittel, Phys. Reports 270 (1996) 1.

[8] E.K. Sarkisyan *et al.*, Phys. Lett. B 347 (1995) 439; G.L. Gogiberidze *et al.*, Proc. 8th Int. Workshop on Multiparticle Production, *Correlations and Fluctuations '98: From QCD to Particle Interferometry* (Mátraháza, 1998), T. Csörgő *et al.* (Eds.), World Scientific, 1999, p. 498.

[9] D. Ghosh *et al.*, Z. Phys. C 71 (1996) 243; S.-S. Wang, R. Liu, Z.-M. Wang, Phys. Lett. B 438 (1998) 353.

[10] A. Abdurakhimov *et al.*, Instrum. Exp. Tech. 21 (1979) 1210.

[11] M. Anikina *et al.*, Phys. Rev. C 33 (1986) 895.

[12] L. Chkhaidze *et al.*, J. Phys. G 22 (1996) 641.

[13] SKM-200 Collab., M. Anikina *et al.*, JINR report E1-84-785 (1984); JINR Rapid Commun. 1[34] (1989) 12.

[14] A. Białas and M. Gazdzicki, Phys. Lett. B 252 (1990) 483;
W. Ochs, Z. Phys. C 50 (1991) 339.

[15] R. Brockmann *et al.*, Phys. Rev. Lett. 53 (1984) 2012.

[16] S. Nagamia and M. Gyulassy, Adv. Nucl. Phys. 13 (1984) 201.

[17] S. Backović *et al.*, JINR Rapid Comm. 2[53] (1992) 58.

[18] J. Chiba *et al.*, Phys. Rev. Lett. 67 (1991) 1982.

[19] R.M. Weiner, Phys. Reports (to appear), `hep-ph/9904389`.